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Search for a Structure in the $B_s^0\pi^\pm$ Invariant Mass Spectrum with the ATLAS Experiment

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A search for the narrow structure, $X(5568)$, reported by the D0 Collaboration in the decay sequence $X \to B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$, is presented. The analysis is based on a data sample recorded with the ATLAS detector at the LHC corresponding to 4.9 fb^{-1} of pp collisions at 7 TeV and 19.5 fb^{-1} at 8 TeV. No significant signal was found. Upper limits on the number of signal events, with properties corresponding to those reported by D0, and on the X production rate relative to B_s^0 mesons, ρ_X, were determined at 95% confidence level. The results are $N(X) < 382$ and $\rho_X < 0.015$ for B_s^0 mesons with transverse momenta above 10 GeV, and $N(X) < 356$ and $\rho_X < 0.016$ for transverse momenta above 15 GeV. Limits are also set for potential $B_s^0\pi^\pm$ resonances in the mass range 5550 to 5700 MeV.

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The D0 Collaboration reported evidence of a narrow structure, $X(5568)$, in the decay $X \to B_s^0\pi^\pm$ with $B_s^0 \to J/\psi\phi$ in proton-antiproton collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV at the Tevatron collider [1]. The structure was interpreted as a tetraquark with four different quark flavors: b, s, u, and d. The mass and natural width of this state were fitted to be $m = 5567.8 \pm 2.9(\text{stat})^{+0.9}_{-1.9}(\text{syst})$ and $\Gamma = 21.9 \pm 6.4(\text{stat})^{+5.0}_{-2.5}(\text{syst})$ MeV, respectively, and the signal significance is 5.1σ. The ratio ρ_X of the yield of $X(5568)$ to the yield of the B_s^0 meson for a transverse momentum range $10 < p_T(B_s^0) < 30$ GeV was measured to be $0.086 \pm 0.019(\text{stat}) \pm 0.014(\text{syst})$. The result initiated a discussion of the nature of the new state and prospects for observation of other tetraquark hadrons [2–6]. Recently, the D0 Collaboration reported further evidence for the resonance $X(5568)$ [7] in the decay sequence $X \to B_s^0\pi^\pm$, $B_s^0 \to \mu^\mp\nu D_s^\pm$, $D_s^\pm \to \phi\pi^\pm$, which is consistent with their previous measurement [1]. However, searches for $X(5568)$ in decays to $B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$ performed by the LHCb [8] and CMS [9] Collaborations in proton-proton (pp) collisions at the LHC and by the CDF Collaboration [10] at the Tevatron, revealed no signal. The upper limits $\rho_X < 0.024$ [LHCb, $p_T(B_s^0) > 10$ GeV], $\rho_X < 0.011$ [CMS, $p_T(B_s^0) > 10$ GeV] and $\rho_X < 0.010$ [CMS, $p_T(B_s^0) > 15$ GeV] at 95% confidence level (C.L.) were determined within the acceptances of the LHCb and CMS experiments. CDF set an upper limit $\rho_X < 0.067$ at 95% C.L. within a kinematic range similar to that of D0 [1].

In this Letter, a search for the $X(5568)$ state by the ATLAS experiment at the LHC is presented (B_s^0 refers to both the B_s^0 and $\bar{B}_s^0$ mesons). The B_s^0 mesons are reconstructed in their decays to $J/\psi(\mu^+\mu^-)\phi(K^+K^-)$. The analysis is based on a combined sample of pp collision data at $\sqrt{s} = 7$ and 8 TeV corresponding to integrated luminosities of 4.9 and 19.5 fb^{-1}, respectively. The ATLAS detector [11] covers nearly the entire solid angle around the collision point with layers of tracking detectors, calorimeters, and muon chambers. The muon and tracking systems are of particular importance in the reconstruction of B mesons. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids with eight coils each, a system of tracking chambers, and detectors for triggering. To study the detector response, to estimate backgrounds, and to model systematic effects, 12×10^6 Monte Carlo (MC) simulated $B_s^0 \to J/\psi\phi$ and 1×10^6 $B_s^0\pi^\pm$ events were generated using Pythia 8.183 [12,13] tuned with ATLAS data [14]. Multiple overlaid proton-proton collisions (pileup) were simulated with Pythia soft QCD processes. The detector response was simulated using the ATLAS simulation framework [15] based on GEANT4 [16]. The MC events were weighted to reproduce the same pileup and trigger conditions as in the data. As in the D0 analysis [1], the $B_s^0\pi^\pm$ resonance was generated using the Breit-Wigner (BW) parametrization appropriate for an S-wave two-body decay near threshold:

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$$F_{\rm BW}(m(B_s^0\pi^\pm), m_X, \Gamma_X) = \frac{m(B_s^0\pi^\pm) m_X \Gamma(m(B_s^0\pi^\pm), \Gamma_X)}{(m_X^2 - m^2(B_s^0\pi^\pm))^2 + m_X^2\Gamma^2(m(B_s^0\pi^\pm), \Gamma_X)}, \quad (1)$$

where $m(B_s^0\pi^\pm)$ is the invariant mass of the $B_s^0\pi^\pm$ candidate and m_X and Γ_X are the mass and the natural width of the resonance. The mass-dependent width is $\Gamma(m(B_s^0\pi^\pm), \Gamma_X) = \Gamma_X \times (q_1/q_0)$, where q_1 and q_0 are the magnitudes of the three-vector momenta of the B_s^0 meson in the rest frame of the $B_s^0\pi^\pm$ system at the invariant masses equal to $m(B_s^0\pi^\pm)$ and m_X, respectively. The mass and the width were set to $m_X = 5567.8$ MeV and $\Gamma_X = 21.9$ MeV, as reported in Ref. [1]. The events were selected by the dimuon triggers [17] based on identification of a $J/\psi \to \mu^+\mu^-$ decay, with p_T thresholds of either 4 or 6 GeV, with both symmetric, (4, 4) or (6, 6) GeV, and asymmetric, (4,6) GeV, combinations. In addition, each event must contain at least one reconstructed primary vertex (PV), formed from at least six ID tracks. The selection of J/ψ and $\phi \to K^+K^-$ candidates is identical to the one described in detail in Ref. [18]. Candidates for $B_s^0 \to J/\psi\phi$ decays are selected by fitting the tracks for each combination of $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ to a common vertex. The fit is further constrained by fixing the invariant mass of the two muon tracks to the J/ψ mass [19]. A quadruplet of tracks is accepted for further analysis if the vertex fit has a $\chi^2/\text{d.o.f.} < 3$. For each B_s^0 meson candidate the proper decay time t is extracted using the method described in Ref. [18]. Events with $t > 0.2$ ps are selected to reduce the background from the events with a J/ψ produced directly in the pp collision. If there is more than one accepted B_s^0 candidate in the event, the candidate with the lowest $\chi^2/\text{d.o.f.}$ of the vertex fit is selected. For the selected events the average number of proton-proton interactions per bunch crossing is 21, necessitating a choice of the best candidate for the PV at which the B_s^0 meson is produced. The variable used is the three-dimensional impact parameter d_0, which is calculated as the distance between the line extrapolated from the reconstructed B_s^0 meson vertex in the direction of the B_s^0 momentum, and each PV candidate. The chosen PV is the one with the smallest d_0. Using MC simulation it was shown that the fraction of B_s^0 candidates that are assigned the wrong PV is less than 1% [18] and that the corresponding effect on the results is negligible. Finally, a requirement that the B_s^0 transverse momentum is greater than 10 GeV is applied. Figure 1 shows the reconstructed $J/\psi K^+K^-$ mass distribution and the result of an extended unbinned maximum-likelihood fit in the range (5150–5650) MeV, in which the signal is modeled by a sum of two Gaussian distributions and an exponential function is used to model the combinatorial background. The observed signal width is consistent with MC simulation. The fitted B_s^0 mass is $m_{\rm fit}(B_s^0) = 5366.6 \pm 0.1$ (stat) MeV, in agreement with the world average value 5366.89 ± 0.19 MeV [19]. For further investigation, only candidates with a reconstructed mass in the signal region 5346.6–5386.6 MeV are included, which gives $N(B_s^0) = 52750 \pm 280$ (stat) candidates.

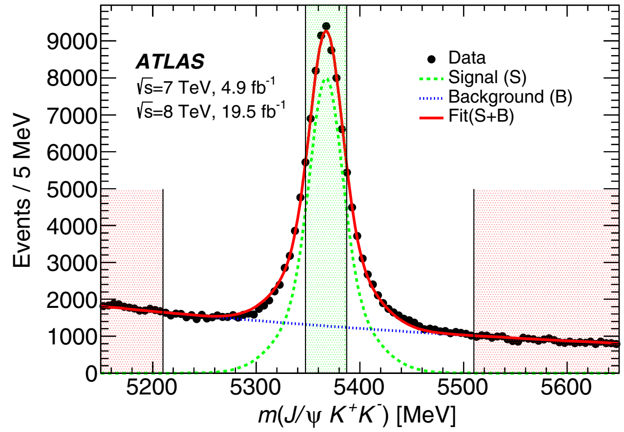

FIG. 1. The invariant mass distribution for $B_s^0 \to J/\psi\phi$ candidates satisfying the selection criteria. Data are shown as points and results of fits to signal (dashed), background (dotted), and the total fit (solid) are shown as lines. The two outer (red) shaded bands and the central (green) shaded band represent the mass sidebands and the signal region of B_s^0 meson candidates, respectively.

The $B_s^0\pi^\pm$ candidates are constructed by combining each of the tracks forming the selected PV with the selected B_s^0 candidate. Tracks that were already used to reconstruct the B_s^0 candidate and tracks identified as leptons (e or μ) are excluded, as well as tracks with transverse momentum $p_T < 500$ MeV. This p_T selection was chosen to maximize the ratio of the $B_s^0\pi^\pm$ signal to the background, based on MC simulation. Assigning the pion mass hypothesis to the tracks that pass these selection criteria, the mass $m(B_s^0\pi^\pm)$ is calculated as $m(J/\psi KK\pi^\pm) - m(J/\psi KK) + m_{\rm fit}(B_s^0)$, where $m_{\rm fit}(B_s^0) = 5366.6$ MeV. On average there are 1.8 $B_s^0\pi^\pm$ candidates in each selected event and all are retained for the analysis. A systematic study has shown that the effect on the results due to multiple candidates is negligible. The mass distribution of $B_s^0\pi^\pm$ candidates is fitted using an extended unbinned maximum-likelihood method. The probability density function (PDF) for the background component is defined as a threshold function:

$$F_{\rm bck}(m(B_s^0\pi^\pm)) = \left(\frac{m(B_s^0\pi^\pm) - m_{\rm thr}}{n}\right)^a \times \exp\left(\sum_{i=1}^{4} p_i \left(\frac{m(B_s^0\pi^\pm) - m_{\rm thr}}{n}\right)^i\right), \quad (2)$$

where $m_{\rm thr} = m_{\rm fit}(B_s^0) + m_\pi$ and n, a, and p_i are free parameters of the fit. The background PDF was tested using

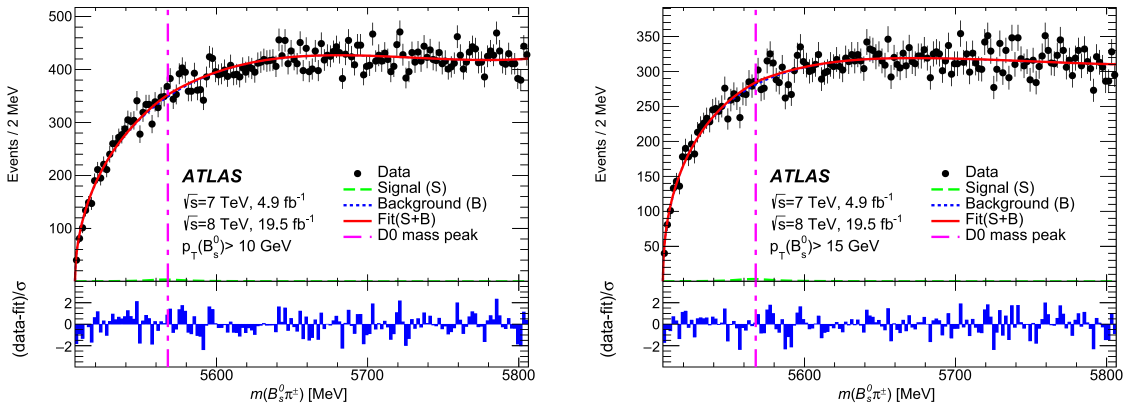

FIG. 2. Results of the fit to the $B_s^0\pi^\pm$ mass distribution for candidates with $p_T(B_s^0) > 10$ GeV (left) and $p_T(B_s^0) > 15$ GeV (right). The bottom panels show the difference between each data point and the fit divided by the statistical uncertainty of that point.

events with no real $B_s^0\pi^\pm$ candidates from two categories. The first background sample contains data events where $B_s^0\pi^\pm$ candidates are formed using "fake" B_s^0 mesons from the mass sidebands, shown in Fig. 1 by red shaded bands, defined as $5150 < m(J/\psi K^+K^-) < 5210$ MeV and $5510 < m(J/\psi K^+K^-) < 5650$ MeV. The second background sample is modeled using MC events containing only B_s^0 mesons not originating from the $B_s^0\pi^\pm$ signal, tuned to reproduce the B_s^0 transverse momentum distribution in data. In these events the B_s^0 meson is combined with each of the tracks originating from the selected PV. The first sample is normalized to the fitted number of B_s^0 background events in the B_s^0 mass signal region 5346.6–5386.6 MeV, while the second sample is normalized to the fitted number of B_s^0 signal events in the same region. The sum of these two distributions is consistent with the distribution of the data. The function in Eq. (2) describes both background distributions as well as their sum within uncertainties. The signal PDF $F_{\rm sig}(m(B_s^0\pi^\pm))$ is defined as a convolution of an S-wave Breit-Wigner PDF, defined in Eq. (1), and the detector resolution represented by a Gaussian function with a width that is calculated individually for each $B_s^0\pi^\pm$ candidate from the tracking and vertexing error matrices. Using MC and data samples, it has been verified that the per candidate mass resolutions are the same for the $B_s^0\pi^\pm$ signal and for the background events passing the selection criteria. The average resolution for the $B_s^0\pi^\pm$ signal, with the mass and width corresponding to those of the structure reported by the D0 Collaboration ($m_X = 5567.8$ MeV and $\Gamma_X = 21.9$ MeV), is 3.2 MeV. The full probability function used is

$$F(m(B_s^0\pi^\pm)) = N(X)F_{\rm sig}(m(B_s^0\pi^\pm)) + [N_{\rm can} - N(X)]F_{\rm bck}(m(B_s^0\pi^\pm)), \quad (3)$$

where $N(X)$ is the number of signal events and $N_{\rm can}$ is the number of all selected $B_s^0\pi^\pm$ candidates. The signal mass and width are fixed to the central values reported by the D0 Collaboration. Following other experiments, fits are performed for two subsets of $B_s^0\pi^\pm$ candidates, first with $p_T(B_s^0) > 10$ GeV and second with $p_T(B_s^0) > 15$ GeV. The results of the fits are shown in Fig. 2 and summarized in Table I. No significant $X(5568)$ signal is observed. Additional selections such as cuts on the angle between the momenta of the B_s^0 and $\pi^\pm$ candidates were investigated and did not produce evidence of a signal. These were found to introduce peaking background so are not included in the analysis. The yields $N(X)$ and $N(B_s^0)$ obtained from the fits are used to evaluate the X production rate relative to B_s^0, within the ATLAS acceptance, using the formula

$$\rho_X \equiv \frac{\sigma(pp \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})} = \frac{N(X)}{N(B_s^0)} \times \frac{1}{\epsilon^{\rm rel}(X)}, \quad (4)$$

where σ represents the production cross section for each of the particles, within the ATLAS acceptance, and the relative efficiency $\epsilon^{\rm rel}(X) = \epsilon(X)/\epsilon(B_s^0)$ is the selection efficiency for the state X, decaying to $B_s^0\pi^\pm$, relative to that for the B_s^0 meson and accounts for the reconstruction and selection

TABLE I. Yields of B_s^0 and $X(5568)$ candidates obtained from the fits to the B_s^0 and $B_s^0\pi^\pm$ candidate mass distributions, with statistical uncertainties. The values given for $N(B_s^0)$ are those inside the B_s^0 signal window. The reported values for $X(5568)$ are obtained from the fits with signal mass and width parameters fixed to those reported by the D0 Collaboration. The relative efficiencies $\epsilon^{\rm rel}(X)$ and their uncertainties are described in the text.

$N(B_s^0)/10^3$	$p_T(B_s^0) > 10$ GeV	52.75 ± 0.28
	$p_T(B_s^0) > 15$ GeV	43.46 ± 0.24
$N(X)$	$p_T(B_s^0) > 10$ GeV	60 ± 140
	$p_T(B_s^0) > 15$ GeV	-30 ± 150
$\epsilon^{\rm rel}(X)$	$p_T(B_s^0) > 10$ GeV	0.53 ± 0.09
	$p_T(B_s^0) > 15$ GeV	0.60 ± 0.10

efficiency of the companion pion, including the soft pion acceptance.

The relative efficiency, $\epsilon^{\rm rel}(X)$, was determined using MC simulation of events containing $X \to B_s^0\pi^\pm$ and B_s^0 decays. In the ratio, the acceptance of the B_s^0 decay cancels, so the value to be determined is the pion reconstruction efficiency for $B_s^0\pi^\pm$ events in which the B_s^0 meson satisfies acceptance, reconstruction, and selection criteria. Based on MC events, $\epsilon^{\rm rel}(X)$ is determined as a function of $p_T(B_s^0)$ and of $m(B_s^0\pi^\pm)$. Using an MC-based function, the acceptance is determined individually for each $B_s^0\pi^\pm$ candidate, based on its measured values of $p_T(B_s^0)$ and $m(B_s^0\pi^\pm)$. The acceptance ratio, $\epsilon^{\rm rel}(X)$, is calculated as an average over the events included in the $m(B_s^0\pi^\pm)$ interval within which the search for a resonance is performed. The width of this interval is defined by a BW function convolved with the mass resolution function, with the start and end points of the range chosen to include 99% of the signal events. The uncertainty of $\epsilon^{\rm rel}(X)$ is calculated by varying the fitted parameters of the MC-based function used to describe the acceptance as a function of $p_T(B_s^0)$ within their uncertainties. Small variations of this function due to the pseudorapidity of the B_s^0 were investigated and are included in the systematic uncertainties. The error also includes the uncertainty in the number of data events used in the average and the statistical uncertainty in the $p_T(B_s^0)$ distribution of these events. The error in the pion reconstruction efficiency, arising from uncertainties in the amount of ID material, is found to have a negligible effect on ρ_X.

As no significant signal is observed, corresponding to the properties of the $X(5568)$ as reported by Ref. [1], upper limits are determined for the number of $B_s^0\pi^\pm$ signal events, $N(X)$, and for the relative production rate, ρ_X. These are calculated using the asymptotic approximation from the profile likelihood formalism [20] based on the $\mathrm{CL_s}$ frequentist method [21]. To establish the limit on the number of $B_s^0\pi^\pm$ signal events, the PDF models for signal and background, defined respectively by Eqs. (1) and (2), are used as inputs to the $\mathrm{CL_s}$ method. Without systematic uncertainties, the extracted upper limits at 95% C.L. are $N(X) < 264$ for $p_T(B_s^0) > 10$ GeV and $N(X) < 213$ for $p_T(B_s^0) > 15$ GeV. Systematic uncertainties affecting these limits are included in the determination of $N(X)$. To obtain results that can be compared to the state $X(5568)$ reported by the D0 Collaboration, systematic uncertainties are assigned by varying the values of m_X and Γ_X independently within Gaussian constraints, with uncertainties equal to those quoted in Ref. [1]. The default model of the X resonance, which is assumed to be spinless, is changed to a BW P-wave resonance. To include the systematic uncertainty due to the modeling of the background, the default PDF of Eq. (2) is replaced by a seventh-order Chebyshev polynomial, allowing more free parameters in the fit. For the detector resolution, the default per-candidate mass resolution model is replaced by the sum of three Gaussian functions with a common mean. The parameters used are determined from the $B_s^0\pi^\pm$ MC sample. Using these alternative models, upper limits that include systematic uncertainties are extracted, leading to values $N(X) < 382$ for $p_T(B_s^0) > 10$ GeV and $N(X) < 356$ for $p_T(B_s^0) > 15$ GeV. To extract the upper limits on ρ_X additional systematic uncertainties are included. The calculation of ρ_X also depends on the precision of extracting the number of B_s^0 signal events and the relative efficiency $\epsilon^{\rm rel}(X)$. To include these uncertainties, the central values and the uncertainties of the number of B_s^0 signal events and $\epsilon^{\rm rel}(X)$ are used to construct Gaussian constraints, which are included as additional inputs to the $\mathrm{CL_s}$ method. Both the statistical and systematic uncertainties are included after being summed in quadrature. For the B_s^0 signal, the default fit model of two Gaussian functions is changed to a triple Gaussian function and the change in the result is taken as a systematic uncertainty. The uncertainty due to the proper decay time requirement $t > 0.2$ ps was estimated by varying it within the time resolution and found to be negligible. The resulting upper limits at 95% C.L. are $\rho_X < 0.015$ for $p_T(B_s^0) > 10$ GeV and $\rho_X < 0.016$ for $p_T(B_s^0) > 15$ GeV. A hypothesis test is performed for the presence of a $B_s^0\pi^\pm$ peak for every 5 MeV step in its mass from 5550 to 5700 MeV, assuming a resonant state as described by Eq. (1), with a BW width of 21.9 MeV [1] and $p_T(B_s^0) >$ 10 GeV. For each $B_s^0\pi^\pm$ mass tested, $\epsilon^{\rm rel}(X)$ is calculated using the same method as for $X(5568)$. The values of $\epsilon^{\rm rel}(X)$ vary from 0.50 to 0.55 in the search interval. The upper limit of ρ_X at 95% C.L. is determined for each tested

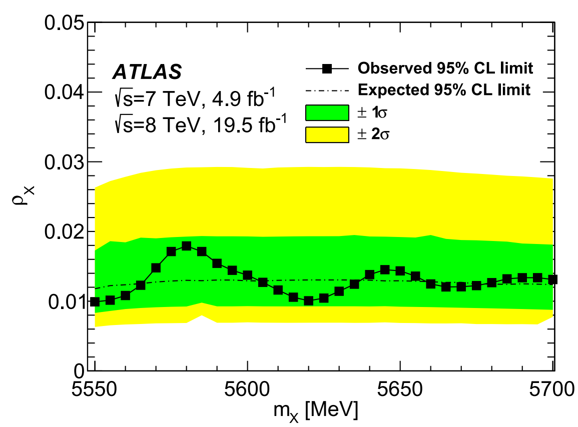

FIG. 3. Upper limits on ρ_X at 95% C.L. (black squares connected by line) at different masses of a hypothetical resonant state X decaying to $B_s^0\pi^\pm$, for events with $p_T(B_s^0) > 10$ GeV. A BW width of $21.9 \pm 6.4(\mathrm{stat})^{+5.0}_{-2.5}(\mathrm{syst})$ MeV is assumed, as reported by D0. The values include systematic uncertainties. The expected 95% C.L. upper limits (central black dot-dashed line) with $\pm1\sigma$ (green) and $\pm2\sigma$ (yellow) uncertainty bands on ρ_X are shown as a function of the assumed resonance mass.

mass. The same systematic uncertainties as in the determination of ρ_X for the state $X(5568)$ are included, with the exception of the $X(5568)$ mass uncertainty. The median expected upper limit at 95% C.L. as a function of the $B_s^0\pi^\pm$ mass is also determined with $\pm 1\sigma$ and $\pm 2\sigma$ error bands. The results are shown in Fig. 3.

In conclusion, a search for a new state $X(5568)$ decaying to $B_s^0\pi^\pm$, with properties as reported by the D0 Collaboration, was performed by the ATLAS experiment at the LHC, using 4.9 fb^{-1} of pp collision data at 7 TeV and 19.5 fb^{-1} at 8 TeV. No significant signal was found. Within the acceptance in which this analysis is performed, upper limits on the number of signal events, $N(X)$, and on the X production rate relative to B_s^0 mesons, were determined at 95% C.L., resulting in $N(X) < 382$ and $\rho_X < 0.015$ for $p_T(B_s^0) > 10$ GeV, and $N(X) < 356$ and $\rho_X < 0.016$ for $p_T(B_s^0) > 15$ GeV. Limits are also set for potential $B_s^0\pi^\pm$ resonances in the mass range from 5550 to 5700 MeV. Across the full range, the upper limit set on ρ_X at 95% C.L. varies between 0.010 and 0.018, and does not exceed the $\pm 1\sigma$ error band from the expected limit.

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